Soil Moisture Evaluation

May 1956 ARS 41-6
Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE

SOIL MOISTURE EVALUATION

M. D. Thorne and W. A. Raney

Since soils vary widely in their ability to hold moisture, it is impossible to establish a direct relationship between plant response and the moisture content of the soil which will hold for soils of different texture. For example, corn may wilt in a clay soil having a moisture content of 15 percent, yet it may suffer from too much water in a sand at 15 percent moisture. In this example, the clay at 15 percent moisture might be at a moisture content less than the wilting percentage and the sand at 15 percent moisture might be wetter than field capacity. It was not until the development of the energy concept of soil moisture that the measuring tools were available for evaluating the degree of availability of water to plants.

Anyone who has squeezed water from a sponge has learned that as water is removed, increasingly greater effort must be expended to get the next bit of water out of the material. While there are basic differences between soil and a sponge, the soil is similar to a sponge in that as more and more water is removed from the soil by plants or by any other means, increasingly greater effort is required to remove the next amount.

The work which a plant root must do in order to extract water from a soil gives an accurate measurement of the availability of the soil moisture to the plant. Techniques have been developed for determining the amount of water removed from soil by a given amount of work. If it is assumed that the plant root would have to do an equal amount of work to get the same amount of water from the soil, we have a means of determining the degree of availability of water in soil.

The pressure membrane apparatus[5,6] represents one such technique which may be used for determining the work* required to remove water from the soil. The soil is placed inside the apparatus on top of a membrane (sausage casing or porous ceramic plate), which will allow water to flow through it, but will not allow air flow within the range of desired pressures. The soil is saturated with water, the lid is clamped on the apparatus, and air pressure introduced into the chamber above the soil. Water is forced out of the soil, through the membrane. The system is allowed to stay at a constant air pressure until no more moisture comes out, which indicates that the attraction between the soil and water is equal to the pressure which tends to displace water. The apparatus is then dissembled and the moisture content of the soil determined by oven drying. This procedure is repeated at different air pressures and the various moisture contents and corresponding pressures, in units of atmospheres, are plotted on a graph. Suppose, for example, an air pressure of 10 atmospheres were applied (10 times 14.7 lbs./square inch) and the equilibrium moisture content was determined to be 18 percent. This would mean that at a moisture content of 18 percent, the soil moisture was held at a tension of 10 atmospheres.

*Actually, the work per unit mass of water is equal to the product of pressure times the area over which it acts times the distance which water must be moved to get it to the point in question from a point of zero energy, divided by density of water times the volume of water. (Work per unit mass $= \frac{\text{Pressure x Area x Distance}}{\text{Density x Volume}}$). However, since density of water is unity in the metric scale, work per unit mass of water is numerically equal to pressure and we loosely use the pressure term rather than work. Furthermore, since energy of soil moisture as described above is negative, we usually speak of the negative pressure as tension or suction. Consequently, tension, in units of atmospheres, is plotted against moisture content and the resulting curves are called moisture characteristic curves or moisture sorption curves. Technically, tension, the independent variable, should be plotted as the abscissa or horizontal axis, but it has sometimes been customary to plot tension as the ordinate. We should make an effort to achieve uniformity and it is urged that all such curves have tension as the abscissa and moisture content as the ordinate.

Such techniques have shown that the moisture tension at field capacity is approximately 0.06 atmospheres for sands and 0.666 atmospheres for clays. The moisture retained at 0.333 atmospheres is used rather widely as indicative of field capacity. These same techniques have shown that moisture content of soil at the permanent wilting percentage was between 7 and 32 atmospheres, dependent upon soil texture and upon the type of plant which was used as the biological indicator. Since this percentage comes on the portion of the moisture characteristic curve, where a change in pressure produces little change in moisture content, there will be little difference in moisture percentage regardless of which pressure is taken as wilting point. 15 atmospheres is the pressure commonly used for this point.

Typical moisture characteristic curves for a clay, a loam and a sand are given in Figure I. The curve for the clay soil shows release of moisture in fairly even increments as tension increases. The curve for the sandy soil shows a proportionately greater release of moisture at the low tension values than does the curve for the clay. The curve for the loam is intermediate in shape between the other two.

Figure II shows the release curves for these same three soils, but plotted with moisture content expressed as percentage "available moisture" (held at tensions between 15 atmospheres and 1/3 atmosphere). If we look at the tensions corresponding to 50 percent "available" moisture for the three soils, we find that for the clay it is 4.5 atmospheres; for the loam 2 atmospheres, and for the sand 0.75 atmospheres. This information is arranged in Table I for various available moisture percentages.

Irrigation treatment variables should be specified on the basis of maximum tension values allowed rather than on minimum percentages of available moisture. A greatly different crop response would be expected on these three soils if irrigated whenever "available" moisture dropped to 50 percent, since the tension values would be greatly different. If, however, irrigation were applied whenever soil moisture tension reached 2 atmospheres, for example, more comparable yield responses on the three soils might be expected. The roots of the crop would have to exert the same maximum tension to obtain moisture in each case. The average tension would not be the same, however, since the maximum would be reached at different rates in the three soils. The yield responses would still not necessarily be identical. It would, however, give much better basis for transposing response information from one set of conditions to another.

If 2 atmospheres were the maximum tension allowed, the clay would be irrigated when only 25 percent of the available soil moisture had been depleted while the loam would have 50 percent and the sand 75 percent of the available moisture used. Similar values for other tension levels are given in Table II. The amounts of water which would have to be applied to replenish the top foot can be calculated from the moisture characteristic curves and the soil density values. For the three soils referred to, these values are shown in Table III. It is of interest that in the example here the amounts to be applied to the three soils at 2 atmospheres tension are about equal. This would not necessarily be the case for all soils and would obviously depend on the moisture characteristic curve of the soil.

Field Measurement of Soil Moisture is essential in order to conduct an irrigation experiment or a field irrigation program in accordance with the above recommended procedure.

The characteristics of an ideal soil moisture measuring device are:

1. The device is inexpensive so that a large number could be used when they are required because of soil heterogeneity.

2. The device is durable and will not change calibration.

3. The device can be installed in the soil in which plants are growing without significantly affecting the plant.

4. The device is capable of giving a continuous picture of soil moisture conditions.

5. The device should give single valued answers of soil water conditions.

6. There should be no transfer of water from the soil to the device or vice versa.

7. The device should measure soil moisture tension.

These characteristics are met with varying degrees of success. None of the present methods fit all of these characteristics. To date there is only one type of instrument, the tensiometer, which can measure moisture tension directly and it is not satisfactory under many soil-plant conditions. Other methods are used to obtain the moisture tension indirectly. A tensiometer consists essentially of a porous cup filled with water and connected by a continuous water column to a vacuum measuring device, either gauge or manometer. (There

are two types of porous cups which are generally used. The cup which is ceramic, impregnated with plastic, is generally more satisfactory than the one that is entirely ceramic. Porous stainless steel was developed for separation of uranium isotopes by the diffusion process during World War II. The pore sizes of this material are sufficiently small for it to be fabricated into tensiometer cups, but the cost is prohibitive.) The cup is inserted in the soil at the desired depth and measurements are read above ground on the vacuum indicator. They will operate satisfactorily at tensions less than about 3/4 atmosphere. At tensions greater than that, the water column breaks and air enters the cup, rendering the instrument inoperative. For the sand illustrated in Figure I, this might be satisfactory for use in moisture studies, but for the clay it would cover only a small part of the available moisture range. Consequently, tensiometers in the clay soil would be of value only for crops requiring conditions of high soil moisture content or low moisture tension. For the loam illustrated, tensiometers would cover a greater proportion of the available moisture range than for the clay, but not so great as for the sand. One of the most common causes of difficulty with tensiometers results from attempting to use them for soil-plant situations where they are not suitable. Where they are suitable, however, they become an excellent tool for use in soil moisture studies. This type of instrument can be made in a machine shop or can be purchased under different trade names.

A tensiometer which would operate over the entire plant growth range is in an experimental stage. It consists of a clay paste which is placed in a steel jacket, having either a cintered glass or perforated steel window. This instrument is inserted into the soil at the desired depth. As the soil in contact with the instrument dries out, the clay paste inside the instrument dries and contracts. A strain gauge registers the amount of contraction of the clay paste which is related to soil moisture content. As the soil moisture content increases, the reverse relationship exists, within the limits of hysteresis.

With the exception of tensiometer data, all soil moisture measurements must be related to moisture tension by using the moisture characteristic curves which were previously described in Figure I.

<u>Gravimetric procedures</u> are probably the most widely applicable methods of measuring soil moisture content. Techniques and equipment are simple and the inaccuracies in the determination itself are essentially negligible. Since soil is heterogeneous, the problem of sampling can be handled more easily than with any other method. One determination can be made on a composite sample from a large number of places, rather than from a single location. Two or three such composite samples from a plot will generally give quite satisfactory data.

Gravimetric procedures do not give a continuous picture of soil moisture tension and there may be some disturbance to the growing crop in sampling and in walking over the plots. These are more than offset by greater accuracy and reliability of the data.

Other methods than drying and weighing have been suggested for the determination of moisture in a composite sample. These include:

1. Measurement of heat evolved when a field sample is treated with H_2SO_4. (The acid also reacts with organic matter).

2. Measurement of loss in weight when a field sample is treated with CaC_2.

3. Measurement of the volume of soil and moisture in a field sample of constant weight, with an air or water picometer and subsequently calculating moisture content. In this procedure, a specific gravity of 2.65 gms./cc is assumed for soil and 1.0gms./cc is assumed for water.

4. Estimation of moisture from the plasticity of the sample.

Methods of measuring soil moisture in place are based on several different principles.

Inert absorbers operate on the principle that an absorbent material in the soil will attain equilibrium with soil moisture. Soil moisture is evaluated by determining the moisture content of the inert material and relating this to soil moisture content by a calibration curve. Unfired bricks, wooden blocks, unpainted pencils, ceramic soil points, and gypsum soil points have been used.

There is a considerable time lag in reaching equilibrium with all of these materials when soil moisture content changes. A finite transfer of water takes place and the rate at which water is transmitted through soil at high tension is slow. Extremely sluggish response is encountered. Contact between test specimens and the soil must usually be broken and re-established for each measurement. Moisture estimation from inert absorbers is of little value in irrigation research.

Electrical instruments are frequently used for determining soil moisture in the field. They operate on the principle that a change in moisture content produces changes in some electrical property of the soil or of an instrument inserted into the soil. Electrical conductivity, capacitance, heat conductivity, reflection of neutrons, and absorption of gamma rays have been used as the property measured by various methods. The heat conductivity and electrical capacitance methods are seldom used at present since they have not been found to be very satisfactory.

Since the soil solids, liquids and gases have different electrical properties, a number of people investigated the possibility of measuring the resistance of the soil as a menas of evaluating soil moisture. Carbon electrodes were installed and the electrical resistance between the two electrodes measured periodically. The resistance measured with a wheatstone bridge included not only the resistance of the soil, but also the contact resistance between soil and electrodes. Contact resistance was usually the greatest component of the total resistance between electrodes and measurement of actual soil resistance rendered inaccurate.

Payne in England used a liquid contact; he made a well in the soil and filled it with mercury. This was satisfactory for laboratory determinations but not practical for field use.

McCorkle (8) used 3 or 4 electrodes and measured the resistance between all possible pairs. By solving a series of simultaneous equations into which the resistance values were introduced, he eliminated contact resistance.

Bouyoucos and Mick(3) mounted electrodes permanently in a gypsum block. The block was buried and after the block was assumed to be in equilibrium with soil moisture, the resistance was measured with an A.C. bridge which prevented polarization. Since there is a finite transfer of water between the block and the soil as soil moisture changes, there may be a rather serious time lag in response to changes in soil moisture. The blocks are also subject to changes in calibration due to solubility effects of the gypsum. Blocks disintegrate rapidly in poorly drained, poorly aerated, or acid soil and contact between blocks and soil is sometimes difficult to maintain satisfactorily.

In the past ten years, electrical conductivity units composed of plaster of paris[3], nylon[2], plaster of paris - nylon[2], fiberglass[4], and fiberglass - gypsum[7] have been tested. Considerable effort has been spent by various workers in developing and testing these and various other units but none has been found to be entirely satisfactory. Some of them work quite well under certain conditions but they must be calibrated for the soil in which they are used. It must be kept in mind that conductivity units do not measure the energy with which the moisture is held but only a property of the soil or of another medium which may be directly related to soil moisture content or to the energy. One cannot predict accurately the degree of satisfaction to be realized with any of these instruments in a given soil. It is a mistake to assume that a given resistance reading will represent a certain percentage of soil moisture or a certain moisture tension or a certain percentage of available moisture in all soils. At present

it is necessary to calibrate blocks in the field by determining the resistance readings and corresponding soil moisture contents determined by oven drying samples taken in the field from the same relative positions as the block with reference to depth from the soil surface and distance from growing plants. These data may then be plotted on a graph and the best fitting curve drawn through the points. It is well to avoid attempting to fit a curve until data for a number of wetting and drying cycles are secured. Frequently, the points obtained in the first cycle after installation are erratic and it is hopeless to attempt to draw a curve through them.

While the plaster of paris blocks are the cheapest to purchase or to construct and their readings are probably least affected by soluble salts, their performance at lower tension values (higher moisture percentages) is usually not so satisfactory as that of some of the other blocks. For many soils, plaster of paris blocks show very little increase in resistance until tensions much greater than one atmosphere are attained. Consequently, they are of little value under such conditions if data at lower tensions are desired. They can often be used to good advantage for indicating qualitatively the withdrawal of moisture from different soil horizons. Indications are that some of the other types of blocks show an increase in resistance at much lower tensions than the plaster of paris blocks. It is recommended that the use of such blocks be further investigated in field experiments and that data on their performance in relation to actually determined soil moisture values be obtained wherever possible. It is customary to place fertilizer where most of the plant roots will be located, (six to eight inches deep and under the plants). In the humid region, the use of large amounts of fertilizer may render questionable all moisture measurements in the top foot of soil which involve methods based on electrical resistance. Moisture blocks alone should not be used to specify irrigation treatments or to provide any quantitative soil moisture data until their performance under that soil-plant condition has been proved.

Resistance or conductance meters are required for determining in the field the electrical values to be correlated with moisture content, when any of the resistance blocks are used. These meters are of two general types - the Wheatstone bridge type and the A. C. ohmmeter type. The Wheatstone bridge balances a known resistance within the meter against the unknown resistance of the soil block. Balance may be determined by the null sound of a buzzer or by the use of a "magic eye" tube. The former type of balance indicator is sometimes difficult to hear, especially when working at higher resistance values. This may be extremely irritating to the operator of the instrument.

The "magic eye" (cathode ray) tube is difficult to see in bright light outdoors unless a dark hood is placed over the operator or some sort of eye tube is provided. One commercial instrument employing this principle is heavy and bulky as compared to other instruments. Instruments employing the Wheatstone bridge principle make it possible to balance out the capacitance as well as the resistance. The practical advantage of this is the attainment of a sharper balance of the bridge than if resistance alone were balanced, and it may have other theoretical advantages under some conditions.

The A. C. ohmmeter does not depend on circuit balance, but gives a direct indication of the magnitude of current through the soil blocks by means of a pointer moving above a dial. A chart or table may be required to convert this reading to resistance or the reading may be used directly to calibrate the soil units in terms of percent moisture. Meters of this type are generally lighter and more convenient and simple to use in the field. A meter of good quality will give reliable information but some cheaper models of low quality may give misleading data.

Some instruments have been manufactured which have the soil units and the measuring meter incorporated into a single probe for field use. These have not been found to be satisfactory.

Neutron scattering and gamma-ray absorption techniques look promising for field determination of moisture. They are undergoing testing and it is expected that further developments will arise which may make these very suitable methods for use in irrigation experiments. At present, the zone of measurement is not well defined in the neutron reflection method.

The absorption of gamma-rays is dependent on the mass of material the rays encounter. The source can be placed at one position in the soil and the counting tube at another position and absorption between the two determined. Again one is not certain of the boundary of the zone of measurement. Changes in soil bulk density affect the absorption measurement as well as changes in moisture content. If bulk density is constant the measurement is essentially dependent on moisture content and if moisture content is constant it is sensitive to bulk density changes.

<u>Accumulated moisture use values</u> have been used for specifying irrigation applications and in some cases good correlation with scheduling by maximum tension values have been reported. Moisture use values are measured in small plots or tanks designed for the purpose or may be calculated from climatological data. Since experience with this method is limited, it is not recommended for irrigation research

until more information is accumulated. This technique presents the possibility of accurately scheduling irrigations without actually measuring soil moisture. The convenience of this is obvious, but the proof of its feasibility is lacking.

Soil sampling and oven drying must still remain the standard against which other methods of moisture determination are compared. While this method requires a good deal of time and labor, it is capable of providing reliable data. The method of field sampling is important. Precision is increased as the number of samples taken per plot is increased, but facilities available generally limit the extent of sampling. Thorough mixing and accurate subdivision of samples is important. A sample-splitter is a valuable tool for both of these operations. The sample should be run through and recombined a number of times before final subdivision. It is important that the sample taken represents the desired depth and position in relation to the plants. To evaluate the moisture conditions in the plant root zone, a number of samples representing desired depth increments must be taken, or a composite sample representing the depth to the bottom of the root zone used.

If lateral distribution of moisture is to be measured, a number of sampling stations at different distances from the plant line must be used. To calibrate a moisture measuring instrument placed at a 6-inch depth in the plant line, samples should be taken at a 6-inch depth in the plant line and not from a 0 to 12-inch depth for this purpose.

Until the accuracy of other methods is established for the conditions of an experiment, field sampling and oven-drying should be used for determining moisture conditions in the field, the percent moisture being related to tension by the moisture characteristic curve.

FIGURE I

MOISTURE CHARACTERISTIC CURVES

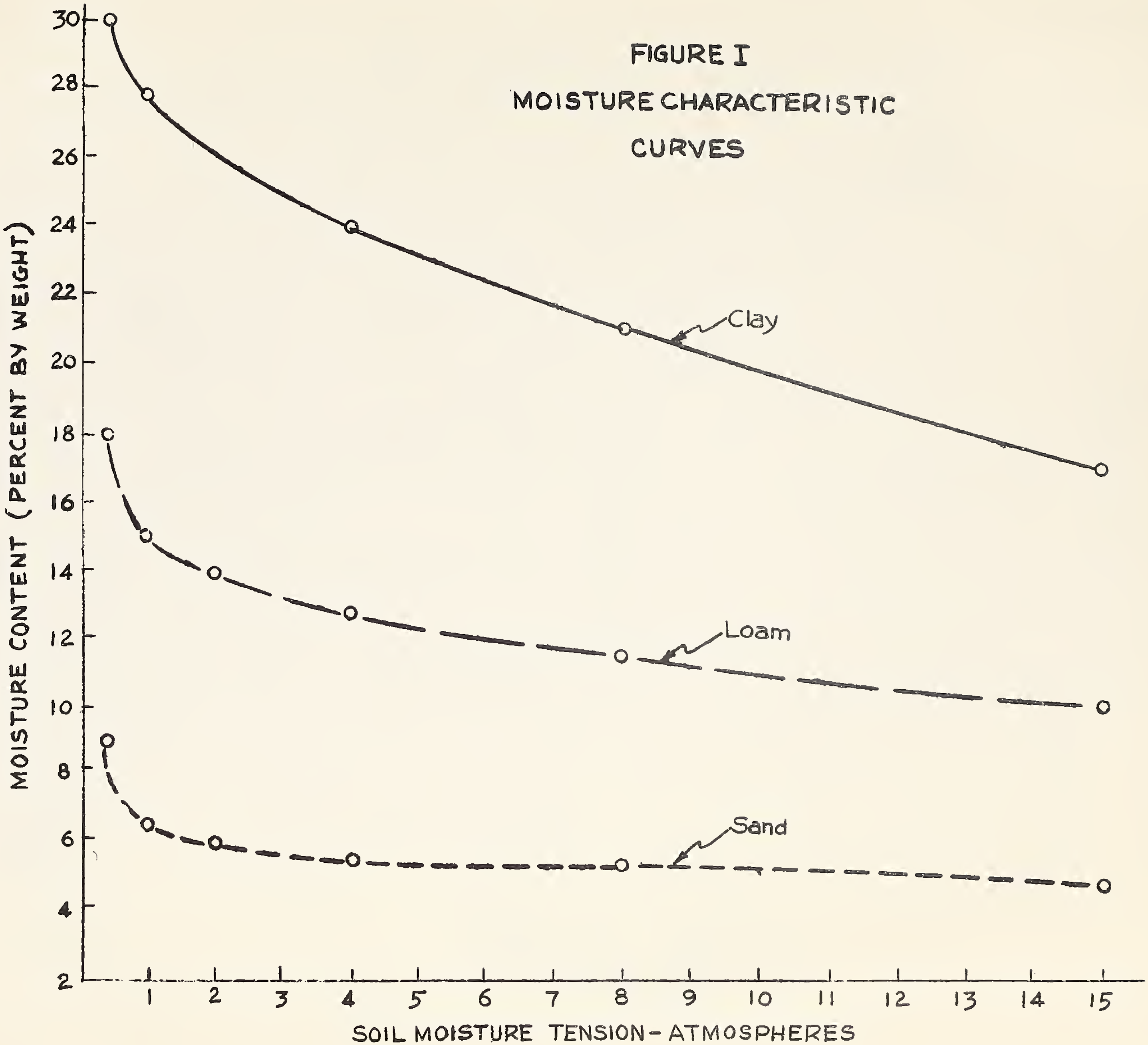

FIGURE II
AVAILABLE MOISTURE
vs TENSION CURVES

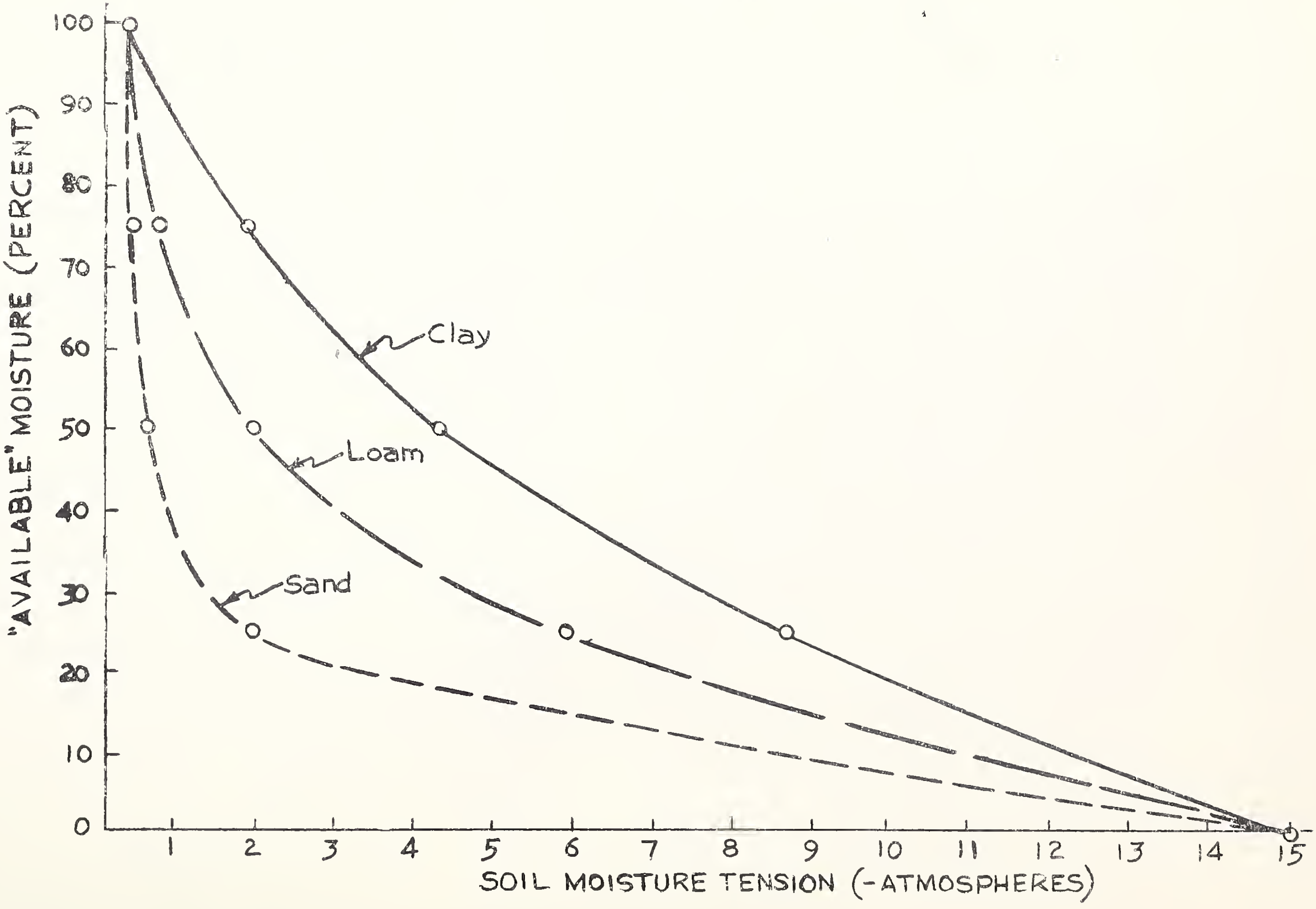

TABLE I

TENSION VALUES AT VARIOUS AVAILABLE MOISTURE CONTENTS

	Percent Available Moisture		
	25	50	75
	(Atm)	(Atm)	(Atm)
Clay	8.8	4.5	1.9
Loam	6.0	2.0	0.8
Sand	2.0	0.8	0.5

TABLE II

AVAILABLE MOISTURE CONTENT AT VARIOUS TENSION LEVELS

	Atmospheres Tension				
	1	2	4	8	15
	%	%	%	%	%
Clay	87	75	52	28	0
Loam	70	50	33	18	0
Sand	40	25	19	13	0

TABLE III

INCHES OF WATER PER FOOT OF SOIL TO REPLENISH IF IRRIGATED AT VARIOUS TENSIONS

	Atmospheres Tension				
	1	2	4	8	15
Clay	0.30	0.58	1.12	1.68	2.34
Loam	0.43	0.72	0.95	1.18	1.44
Sand	0.43	0.54	0.58	0.63	0.72

R E F E R E N C E S

(1) Bouyoucos, G. J. Nylon electrical resistance unit for continuous measurement of soil moisture in the field. Soil Sci. 67, 1949 (319-330). (Mich. Agri. Expt. Sta.)

(2) Bouyoucos, George John. Electrical resistance methods as finally perfected for making continuous measurement of soil moisture content under field conditions. Quarterly Bulletin, Mich. Agri. Expt. Sta. 37:132-149, 1954.

(3) Bouyoucos, G. J. and Mick, A. H. 1940. An electrical resistance method for the continuous measurement of soil moisture under field conditions. Mich. Agri. Expt. Sta. Tech. Bul. 172.

(4) Colman, E. A. and Hendrix, T. M. 1949. The fiberglass electrical soil-moisture instrument. Soil Sci. 67:425-438.

(5) Richards, L. A. 1949. Methods of measuring soil moisture tension. Soil Sci. 68, (95-112).

(6) Richards, L. A. Editor. 1954. Diagnosis and improvement of saline and alkali soils (Method No. 32). U.S.D.A. Agri. Handbook No. 60.

(7) Youker, R. E. and Dreibelbis, F. R. An improved soil-moisture measuring unit for hydrologic studies. June 1951. Trans., Amer. Geo. Union Vol. 32 No. 3 pp. 447-449.

(8) McCorkle, W. H. 1931. Determination of soil moisture by the method of multiple electrodes. Texas Agri. Expt. Sta. Bul. 426.